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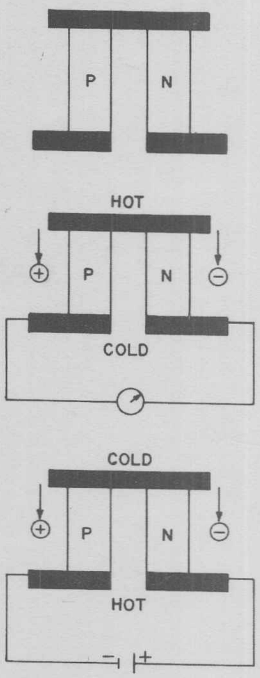
Thermoelectric Devices



APPLICATION NOTES

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APPLICATION NOTES
for
CAMBION THERMOELECTRIC DEVICES

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SPECIFICATIONS OF THERMOELECTRIC MODULES

The two specifications of thermoelectric devices generally considered as basic performance parameters are (1) the maximum heat pumping capacity (Q_c) when Delta T=0 and (2) the maximum Delta T when Q_c=0. CAMBION's philosophy on such specifications is that published data should be in a form which is most useful to the end user or designer and that the data should reflect, as much as possible, the actual conditions under which thermoelectric devices are normally used. Consequently, published module specifications are not ideal or theoretical maximum values but, rather, are minimum values based on a large number of actual modules tested with zinc oxide loaded silicone grease on the module face plates (thus accounting for interface losses).
In addition, specifications are further based on modules operated in a "normal" room atmosphere as opposed to a vacuum. With vacuum operation, performance specifications will be 10 to 15% higher than those published. For example, a single stage module specified as having a maximum Delta T of 60 °C at normal atmospheric pressure will give a Delta T in the range of 66 to 69 °C when tested in a vacuum of at least 10^{-3} torr.

application note

THERMOELECTRIC THEORY

AND

HEAT PUMP PERFORMANCE

INTRODUCTION

To a considerable extent, the inherent capabilities and limitations of thermoelectric devices are governed by the characteristics of available thermoelectric materials and fabrication techniques.

Factors such as temperature limitations, operating efficiency, reliability, durability, size, weight, configuration, power requirements, as well as cost are all related to materials and fabrication considerations.

In order to provide a basis for evaluating the feasibility of thermoelectric technology for specific applications, and for recognizing the possibilities and limitations of current and future technology, it is worthwhile to briefly review some of the relevant concepts. The field is extremely broad and attention will therefore be directed primarily toward qualitatively outlining present boundaries and the various techniques which can be utilized to alter performance. For the purpose of this text it seems appropriate to focus attention on applications involving cooling, or heat pumping, as opposed to power generation, although it will be seen that the concepts and technology are similar.

TYPES OF MATERIALS

In general, materials in the solid state are recognized by their electrical properties as metals, semiconductors, or insulators. The most useful known crystalline materials for thermoelectric elements are classified as semiconductors having an electrical resistivity between the metals and insulators.

The most important material factor--the figure of merit Z--describes a single material by the following relationship:

$$Z = \frac{\alpha^2}{\rho K}$$

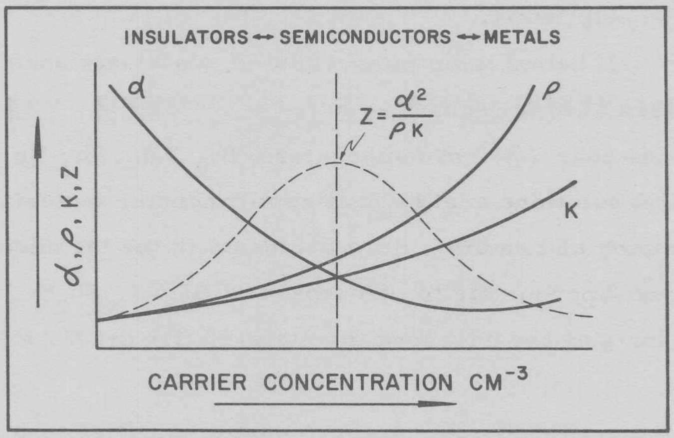
where α = the Seebeck coefficient (μ V/°C)

ρ = resistivity (ohm-centimeter)

K = thermal conductivity (watts/cm°C)

It is evident from this relationship that control of the Seebeck coefficient, electrical resistivity and thermal conductivity is essential to obtain a high figure of merit. All three quantities are a function of the density of free charge carriers.

Many investigators have shown the semiconductor materials to have the highest figure of merit in the region where the carrier concentration is in the order of 10^{-18} to 10^{-21} carriers per cubic centimeter. The relationship of the thermoelectric parameters as a function of the carrier concentration for insulators, semiconductors, and metals can be seen in this sketch:



The electrical conductivity $\sigma = 1/\rho$ increases with increasing carrier concentration and the Seebeck effect decreases with increasing carrier concentration. The thermal conductivity K has two components, a lattice thermal conductivity independent of the carrier concentration and the electronic thermal conductivity which is proportional to the carrier concentration.

Some of the frustrations inherent in finding suitable materials are now apparent. Insulators have high α's but low electrical conductivities! On the other hand metals have α's much too small. The peak value corresponds to near degeneracy for semiconductors.

SELECTION OF MATERIALS

In selecting a suitable semiconductor, it is desirable to achieve a high carrier N, which is generally associated with low Eg. It is important, however, that the band gap be large enough to avoid intrinsic conduction at the highest temperature to be used. Extensive research has led to the conclusion that Bi_2Te_3 and its alloys exhibit the most desirable characteristics for operation near ambient temperatures.

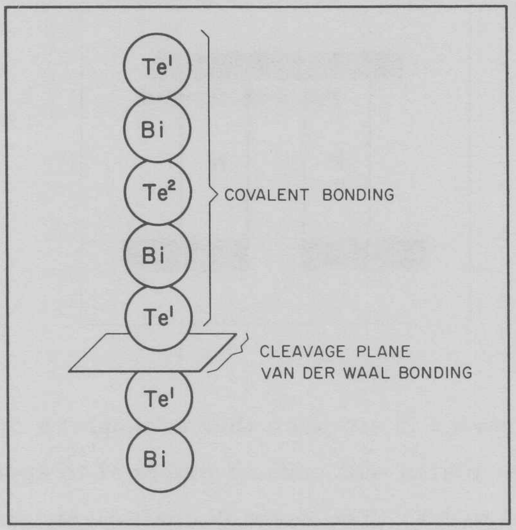
For higher temperature operation, i.e., above 200°C, PbTe is superior for both cooling and power generation. The maximum Z obtained with PbTe is only 1.5×10^{-3} but this maximum value occurs at a temperature level at which the Z for Bi_2Te_3 is considerably lower.

For operation well below room temperatures, materials such as Bismuth Antimony alloys are advantageous.

For applications near ambient temperature, $Bi_2\ TE_3$, $Sb_2\ Te_3$, Sb_2Se_3 and especially their solid solutions are the best semiconductor materials for thermoelectric heat pumping and cooling. Improvements in the techniques of solid solution alloying of $Bi_2\ Te_3$-Sb_2Te_3 (P-type) and Bi_2Te_3-Sb_2Se_3 (N-type) has been the principle factor that has advanced the state-of-the-art for thermoelectric heat pump materials.

A number of features of Bi_2Te_3 deserve comment. Bi_2Te_3 is hexagonal-rhombohedral in crystalline form with a highly developed basal cleavage. This accounts for the highly anisotropic nature of the material. As an example, the ratio of resistivity $\rho_{\parallel} / \rho_{\perp}$ parallel and perpendicular to the C-axis is in the order of 4. The thermoelectric power for both N and P type materials are independent of crystallographic orientation.

Crystals of Bi_2Te_3 are made up of hexagonal layers of like atoms forming the sequence:



The Te and Bi layers are connected by strong covalent bonds, but the neighboring Te layers are held together by weak Van Der Waal type forces.

Consequently, Bi_2Te_3 crystals can be cleaved quite readily along these basal (0001) planes. This material is thus somewhat friable during processing and this must be taken into account for practical device fabrication.

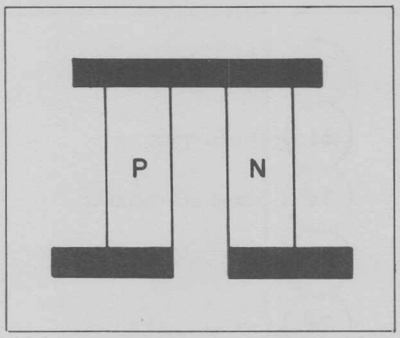
The K is about twice parallel as perpendicular (i.e., ~ .015 w/in $^{\circ}$C), however since the anisotropy of ρ is > K, maximum Z occurs parallel to the basal planes.

The alloys useful as thermoelectric materials are produced either (1) by sintering compressed powders, or (2) by solidification of material from a melt.

Material is generally prepared in the form of homogeneous ingots of large grain size. Homogeneity is an important requirement since the very high concentrations of alloying and doping additions have a tendency to segregate, and/or to precipitate. Both of these result in less than optimum performance. An unexpected natural benefit of Bi_2Te_3, however, is that the material tends to crystallize easily with large grains oriented in the direction exhibiting the best TE characteristics.

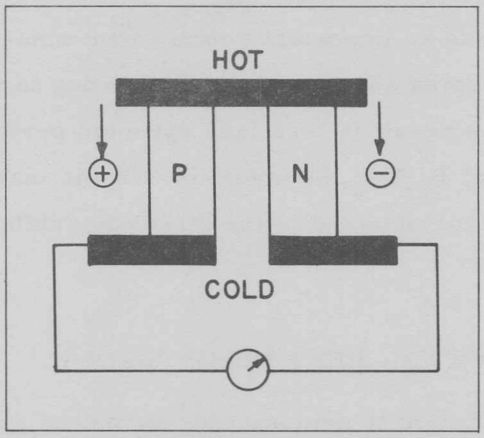
THERMOELECTRIC DEVICES - HEAT PUMP THEORY

A single couple is sufficient to demonstrate the power generation and heat pumping principle.

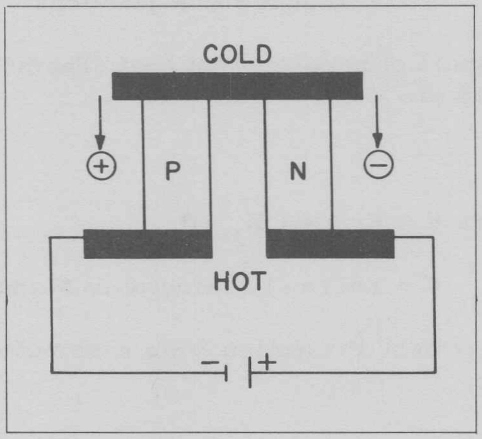


At open circuit this device is simply a thermocouple; a temperature gradient maintained across the plates will cause a potential to appear across the terminals which is proportional to ΔT. The Seebeck coefficient, which is one of the fundamental criteria for thermoelectric performance, is defined as $V/\Delta T$ expressed in μ Volts/^{o}C. It strictly refers to a junction between two materials, but since it is often convenient to refer to Seebeck coefficients of individual materials, measurements are commonly made against a standard, such as lead. P-type material thus has a positive α, N-type a negative α, and the overall junction voltage of P-N couple is equal to αN plus αP.

It should be noted that if a ΔT is maintained and the circuit connected through an electrical load, the Seebeck voltage will cause a current to flow, thus generating power thermoelectrically.



Consider a condition where the circuit is electrically completed through a battery or other DC source:



From the diagram above it can be seen that heat is absorbed at one junction causing it to cool, and heat is rejected at the other junction, causing it to heat. This is simultaneously a TE cooler and heater--in other words, a heat pump. It should be noted that by simply reversing the current, the flow of heat is also reversed.

CONSIDER NOW THE FACTORS AFFECTING THE TE DEVICE PERFORMANCE

Certain assumptions have been made to simplify the theoretical calculations--(1) the problem of heat transfer to the ambient is not considered; (2) it is assumed that the thermal insulation in the device is perfect; (3) it is assumed that the junction resistance is negligible compared to the bulk resistance of the elements; (4) the electrical resistivity ρ, thermal conductivity K, and Seebeck coefficient α, of the materials is assumed independent of temperature.

For α, ρ, and K independent of temperature, the thermal energy delivered to the heat reservoirs in a thermoelectric device has three independent components, namely, the Joule heat, the zero-current heat, and the Peltier heat. The thermal energy transfer to the hot and cold reservoirs in a thermoelectric device is the sum of these three components as follows:

(1) The Joule heat delivered to each reservoir per unit time is:

$$1/2\ I^2 R$$

Where $R = (\rho N/\gamma N)\ (\rho P/\gamma P)$
ρ = Resistivities N and P
γ = A/L of N and P junctions

(2) The rate of transport of zero-current heat (Thomson Effect) between the two reservoirs is:

$$K\Delta T$$

Where $K = K_N \gamma N + K_P \gamma P$

K = Thermal conductivity N and P elements.

(3) The rate of Peltier heat absorption from each reservoir in the simplest case is:

$$Q = I\pi_{PN}$$

π = Peltier coefficient

The rate of heat removal from the cold reservoir can now be expressed as:

$$Q_c = \alpha T_c I - 1/2\ I^2 R - K\Delta T$$

when the derivative of the heat pumping rate, with respect to current is set equal to zero, the current which maximizes the heat pumping rates is found to be:

$$I_{opt} = \alpha T_c / R$$

The applied voltage is:

$$V = \alpha T_h$$

The heat pumping rate at this current is:

$$Q_{c\ max} = \alpha^2\ T_c^{\ 2}/2R - K\Delta T$$

The coefficient of performance of the couple is:

$$C.O.P. = Q_{c\ max}/P$$

Where $P = VI$

From the maximum heat pumping formula it can be seen that the maximum temperature difference which the couple will produce is:

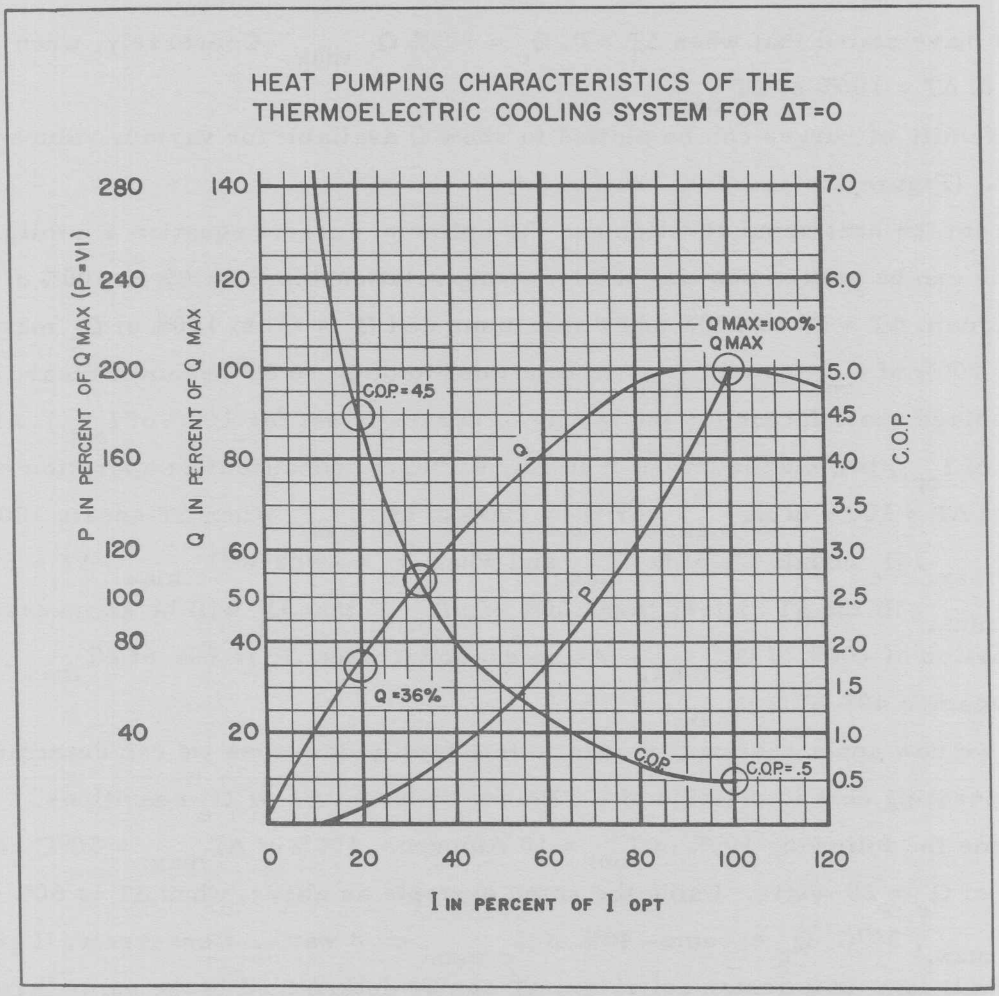
$$\Delta T = \alpha^2 T_c^2 / 2RK$$

The maximum temperature differential can also be expressed as:

$$\Delta T_{max} = 1/2\ Z T_c^2$$

HEAT PUMP PERFORMANCE

The characteristics of thermoelectric couples under $Q_{c\ max}$ conditions will be of interest. From the heat pump equation and the optimum current equation the following relationships can be plotted for $Q_{c\ max}$ ($\Delta T = O$).



If $Q_{c\ max}$ is considered as the maximum heat pumped at I_{opt}, then Q_c and P can readily be determined as a percentage of $Q_{c\ max}$ when the current is given as a percentage of I_{opt} regardless of the actual value of I_{opt}.

In the same manner, C.O.P. will always be the same when the operating current is the same percentage of I_{opt} regardless of the actual value of I_{opt}. As an example, when $Q_{max.}$ = 100%, ΔT = 0, I = 100% I optimum. The C.O.P. is always 0.5. At 20% of I optimum the C.O.P. is always 4.5 and Q = 36% of $Q_{c\ max}$!

MAXIMUM Q_c WHEN ΔT IS NOT ZERO

We have stated that when $\Delta T = 0$, Q_c = 100% $Q_{c\ max.}$ Conversely, when $Q_c = 0$, ΔT = 100% of ΔT_{max}

A family of curves can be plotted to show Q available for various values of ΔT. (Figure 2)

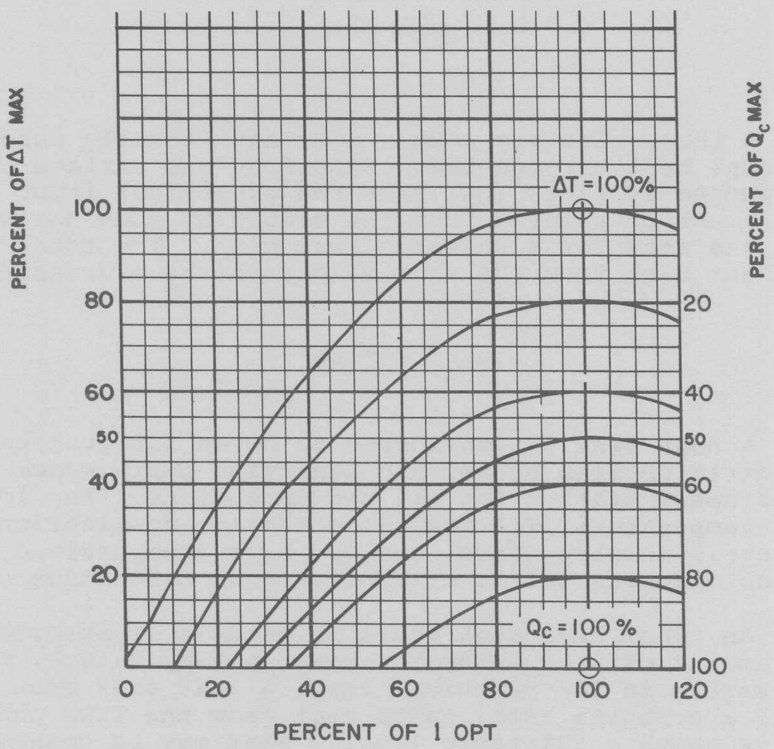
From the heat pump equation and the optimum current equation a family of curves can be plotted showing the following relationships; I = 0% to 100% of I optimum, ΔT = 0% to 100% of ΔT maximum and Q_c = 0% to 100% of Q_c maximum.

At 100% of I_{opt} the direct ratio relationship of Q_c to ΔT becomes clear. (The percentage scale factor for the family of curves is set for 100% of I_{opt}.) At 100% of I_{opt}, two maximum but mutually exclusive conditions of operation can occur; ΔT = 100% of $\Delta T_{max.}$, or Q_c = 100% of $Q_{c\ max.}$ When ΔT equals 100% of $\Delta T_{max.}$, Q_c equals 0% of $Q_{c\ max}$ and when Q_c = 100% of $Q_{c\ max.}$, ΔT = 0% of $\Delta T_{max.}$. If the ΔT is less than 100% of $\Delta T_{max.}$ then Q_c will be an inverse proportion of 100% of $Q_{c\ max.}$. As an example; when ΔT is 60% of $\Delta T_{max.}$, Q_c becomes 40% of $Q_{c\ max.}$.

If we now apply arbitrary values to this family of curves we can determine the operating characteristics of a TED for different ΔT or Q_c conditions. Assume the following 100% of I_{opt} = 10 Amperes, 100% of $\Delta T_{max.}$ = 50°C and 100% of Q_c = 20 watts. Using the same example as above, when ΔT is 60% of $\Delta T_{max.}$, 30°C, Q_c becomes 40% of $Q_{c\ max.}$ or 8 watts. Conversely, if given an 8 watt load as a design criterian, ΔT can be determined in the same manner.

The above criteria are also applicable to any percentage of I optimum. Knowing the value of I to be used, determine $\Delta T_{max.}$ and $Q_{c\ max.}$ for the percentage of I optimum selected. These values of ΔT and Q_c then become the maximum ΔT and Q_c conditions for that percentage of I optimum. The same relationship can then be applied in the same manner as above, to determine the % of Q_c for a given ΔT or the % of ΔT available for a given Q_c at a fixed current input.

HEAT PUMPING CHARACTERISTICS OF THE THERMOELECTRIC COOLING SYSTEM FOR VARIOUS ΔT's



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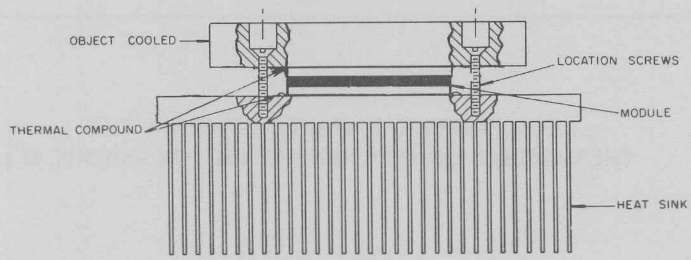
application note

THERMOELECTRIC APPLICATION NOTE

HEAT SINK CONSIDERATIONS FOR THERMOELECTRIC DEVICES



A thermoelectric module does not actually absorb heat, but rather, pumps heat through the module from one surface to the other. The heat pumped in watts (Q_c) plus the electrical input power to the module (P) must be removed from the module by some means, thus dictating the need for a suitable heat sink. The total heat flowing into the heat sink from the module (Q_h) can be expressed by the equation:

$$Q_h = P + Q_c$$

A heat sink is considered to be an integral part of any thermoelectric cooling system and heat sink performance must be taken into consideration for all system designs. The importance of heat sink temperature (T_h) for the effective application of thermoelectric modules (TEDs) can not be overemphasized and all performance characteristics of TEDs vary as a function of T_h.

An ideal heat sink would be capable of absorbing an infinite amount of heat without rising in temperature. Since this is not possible in the practical case, a heat sink must be selected which will absorb the total waste heat from the TEDs and not rise in temperature above a tolerable level. What may be considered as a tolerable level will vary with the application but, because heat pumping capacity of a thermoelectric module decreases as the delta T (ΔT) increases, temperature rise of the heat sink should be minimized as much as possible.

The performance of any heat sink may be specified by its thermal resistance (θ_s), where:

for air cooled systems

$$\theta_s = \frac{\text{temperature rise of heat sink above ambient in °C}}{\text{total input power to heat sink in watts}}$$

or, for liquid cooled systems

$$\theta_s = \frac{\text{temperature rise of heat sink above liquid coolant in °C}}{\text{total input power to heat sink in watts}}$$

Heat sinks are available in several forms including liquid cooled, forced convection, and natural convection types. Liquid cooled heat sinks will generally give superior performance with the thermal resistance typically falling within a range of 0.03°C/watt to 0.2°C/watt. Forced convection types will generally provide a θ_s in the range of 0.07°C/watt to 0.5°C/watt while natural convection heat sinks will frequently fall within a range of 0.6°C/watt to 5.0°C/watt.

Liquid or forced convection methods are strongly recommended for all but extremely low power thermoelectric applications since natural convection heat sinks are not normally efficient enough to give satisfactory results.

Approximate thermal resistance for standard CAMBION heat sinks are listed below.

CAMBION Part No.	Heat Sink Size	Air or Liquid Flow Rate	θ_s
740-0031-01	4.38 X 5 X 1.38"	65 CFM	0.17°C/watt
740-0087-01	4.38 X 8 X 1.38"	65 CFM	0.13°C/watt
803-0049-01	4.75 X 8.5 X 1.38"	110 CFM	0.095°C/watt
806-0205-01	1.25 X 1.25 X 0.5"	300 ml/min	0.17°C/watt
806-0206-01	3.0 X 3.0 X 0.5"	500 ml/min	0.113°C/watt
806-0207-01	3.5 X 5.0 X 0.5"	800 ml/min	0.077°C/watt
806-0208-01	4.75 X 7.5 X 0.5"	1000 ml/min	0.065°C/watt
806-0210-01	11.0 X 13.0 X 0.63"	1500 ml/min	0.050°C/watt

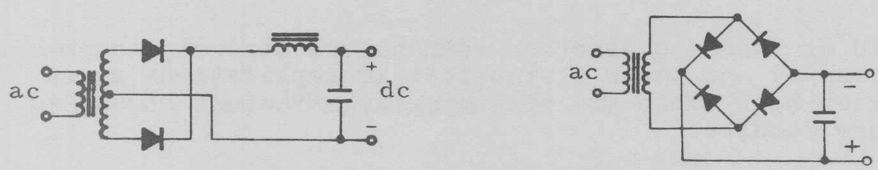
The thermal resistance data shown in the above table is based on the stated air or liquid flow rates, and any increase or decrease in flow rates will cause a resultant change in the θ_s value.

application note

POWER SUPPLY AND TEMPERATURE CONTROL CONSIDERATIONS FOR THERMOELECTRIC DEVICES

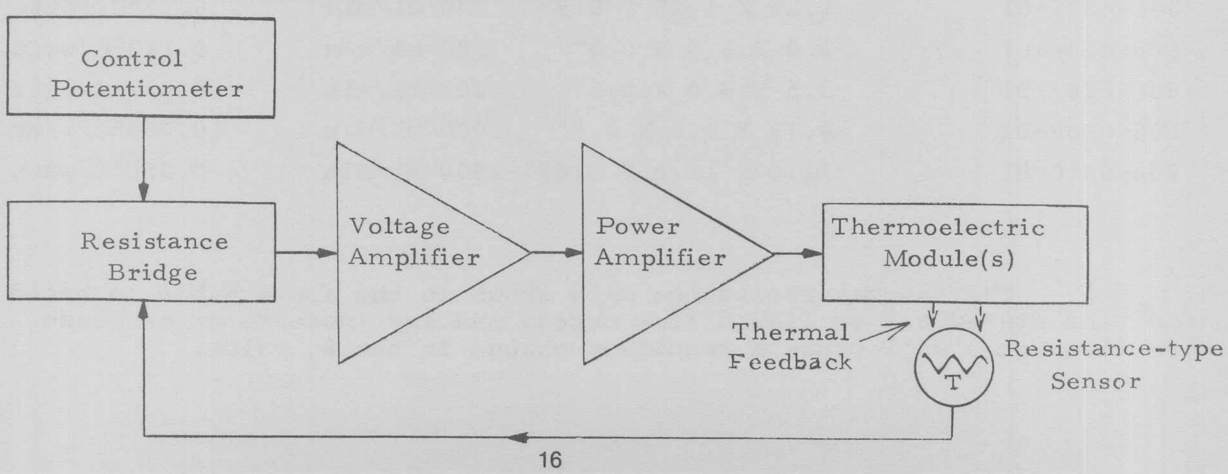
Thermoelectric devices operate from direct current and power requirements are usually not stringent or precise. For most applications, unregulated DC power with a ripple component of 10% or less is satisfactory and it is possible that higher levels of AC ripple car be tolerated for certain non-critical uses. However, because AC ripple will degrade module operating performance, it is generally recommended that the ripple component be limited to 10% or less.

FIGURE I Typical power supply circuits



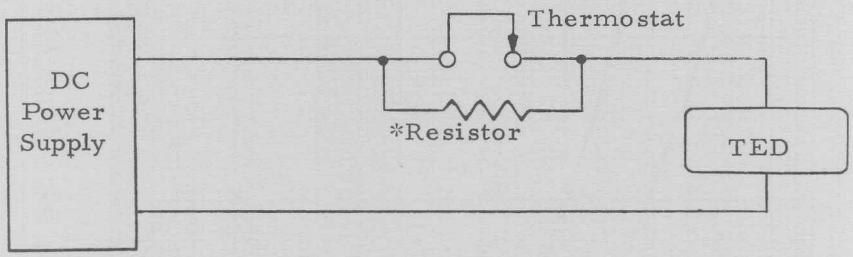
There are many methods of temperature controlling thermoelectric devices and these methods can typically be categorized as either "open-loop" or "closed-loop". With open loop arrangements, manual adjustment of input current is made - normally by means of a variable power supply - and the temperature is thereby maintained reasonably near the desired set-point. With closed-loop methods, a temperature sensor such as a thermocouple, thermistor, or RTD is used to sense the temperature of the thermoelectric device and appropriate electronics effect automatic control of the TED input current. Very precise control may be achieved by this method but relative complexity and cost are greater than for open-loop arrangements.

FIGURE II Typical closed-loop controller



A thermostat may be used when some - but not highly accurate - temperature control is required. If a thermostat is used, it is highly recommended that the circuit illustrated in Figure III be employed in order to avoid frequent and full ON/OFF switching of the input current to the Thermoelectric device. It has been found that when a thermostat is used in the "conventional" manner, premature module failure <u>may</u> occur because of the frequent expansion and contraction resulting from temperature changes produced by the thermostat's open/close differential. With the circuit shown below, full current (or the design maximum) is applied to the thermoelectric module until the thermostat opens. At this point, the resistor is effectively placed in series with the module(s) and the input current is limited to a lower level.

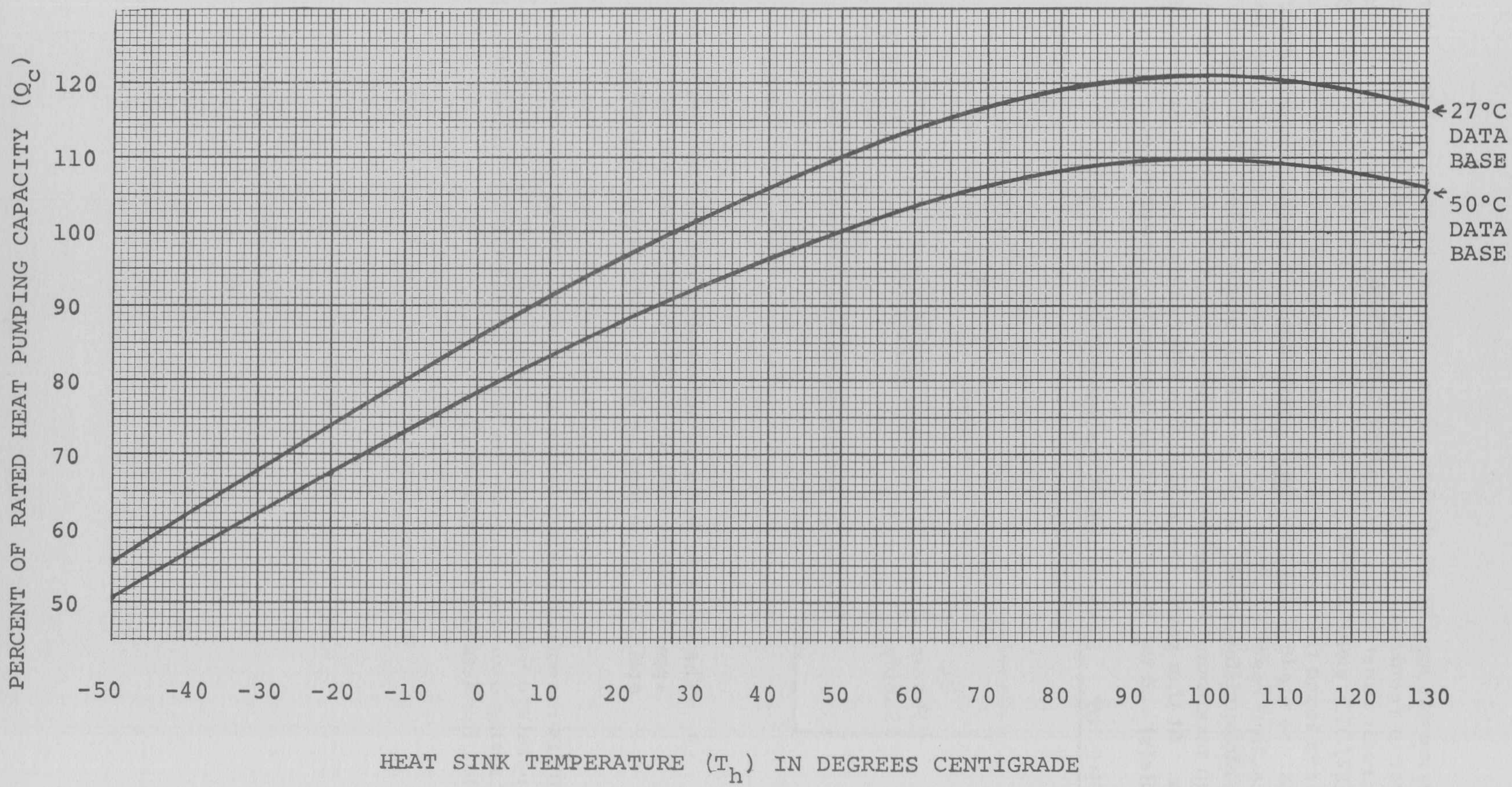
FIGURE III Recommended thermostat control circuit



* The resistor value is selected to reduce the current to approximately 30% of the normal operating level. The optimum value may be determined experimentally.

CAMBION manufactures a number of standard Power Supplies and closed-loop Temperature Controllers designed specifically for driving thermoelectric cooling and heating devices. Consult the latest CAMBION Thermoelectric Product Catalog for detailed information.

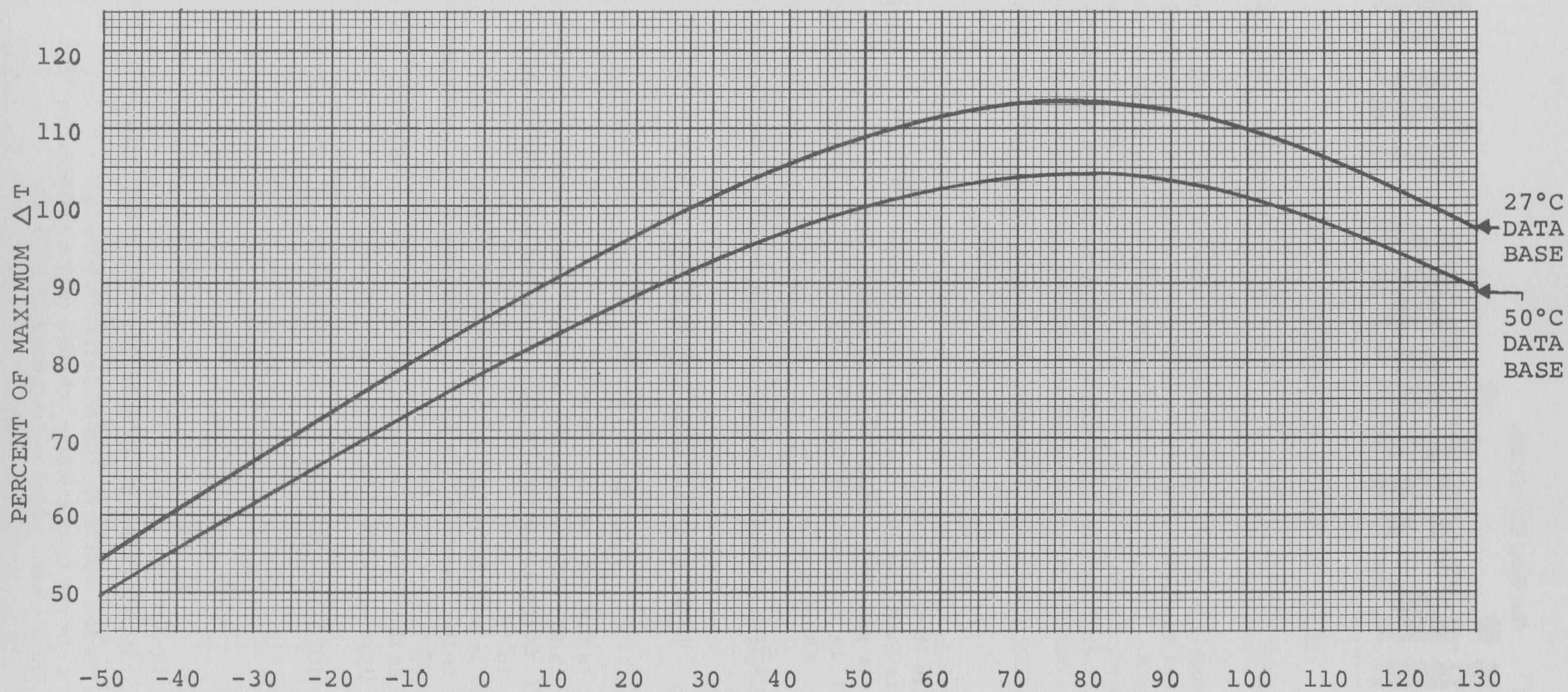
PERCENT OF RATED HEAT PUMPING CAPACITY
FOR VARIOUS HEAT SINK TEMPERATURES



The rated heat pumping capacity of thermoelectric devices is dependent upon the temperature of the heat sink. Performance of TED's at heat sink temperatures other than the specified reference temperatures (normally 27 °C or 50 °C) may be determined from this graph.

PERCENT OF MAXIMUM DELTA T FOR VARIOUS

HEAT SINK TEMPERATURES



HEAT SINK TEMPERATURE (T_h) IN DEGREES CENTIGRADE

The maximum DELTA T of thermoelectric devices is dependent upon the temperature of the heat sink. Performance of TED's at heat sink temperatures other than the specified reference temperatures (normally 27°C or 50°C) may be determined from this graph.

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application note

THERMOELECTRIC APPLICATION NOTE

HEAT TRANSFER FORMULAE FOR THERMOELECTRIC SYSTEM DESIGN

The formulae illustrated in this application note may be used by the layman to estimate thermal requirements for various thermoelectric cooling and heating applications. Due to the relatively complex nature of heat transfer, the results obtained, although useful, must be considered as approximations only. CAMBION'S engineering staff will be happy to provide assistance in more closely determining thermal requirements for your specific application.

A. HEAT LEAKAGE FROM AN EXPOSED SURFACE TO AMBIENT BY CONVECTION

$$Q = h\,A\,\Delta T$$

WHERE: Q is Heat leakage in BTU/HR
h is Heat transfer coefficient in BTU/hr - ft^2 - °F (typical value ≈ 5)
A is exposed surface area in square feet
ΔT is temperature difference between the exposed surface and ambient in °F

B. HEAT LEAKAGE THROUGH THE WALLS OF AN INSULATED CONTAINER

$$Q = A\left[\frac{\Delta T}{\frac{\Delta x}{k} + \frac{1}{h}}\right]$$

WHERE: Q is the heat leakage in BTU/hr
A is the external surface area of the container in square feet
ΔT is the temperature between inside and outside of container in °F
Δx is the thickness of insulation in feet
k is the average thermal conductivity of the insulation in BTU/hr - ft - °F
h is the average heat transfer coefficient in BTU/hr - ft^2 - °F (typical value ≈ 5)

C. TIME REQUIRED TO CHANGE THE TEMPERATURE OF AN OBJECT

$$T = \left[\frac{m\ C_p\ \Delta T}{Q}\right]$$

WHERE: T is the time interval in hours
C_p is the average specific heat of the material in BTU/lb - °F
m is the weight of the material in pounds
ΔT is the temperature change of the material in °F
Q is the heat added or removed in BTU/hr

D. MISCELLANEOUS RELATIONSHIPS

1 Watt = 3.413 BTU/hr

1 BTU/hr = 0.293 watts

$°F = \frac{9}{5}(°C) + 32$

$°C = \frac{5}{9}(°F - 32)$

1 w/cm - °C = 57.80 BTU/hr - ft - °F

1 gm - cal/cm - sec - °C = 242 BTU/hr - ft - °F

1 kg - cal/hr - m^2 - °C/cm = 0.0806 BTU/hr - ft^2 - °F/in

1 cm = 0.3937 in = 0.03281 ft

1 cm^2 = 0.1550 in^2 = 1.076×10^{-3} ft^2

1 cm^3 = 0.06102 in^3 = 3.531×10^{-5} ft^3

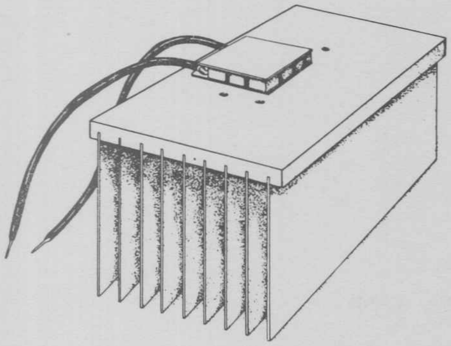
1 gm = 2.205×10^{-3} lbs

1 gm/cm^3 = 62.43 lb/ft^3

E. TYPICAL PROPERTIES OF VARIOUS MATERIALS

MATERIAL	ρ DENSITY lb/ft^3	k THERMAL CONDUCTIVITY BTU/hr - ft - °F	Cp SPECIFIC HEAT BTU/lb - °F
Air	0.074	0.015	0.24
Aluminum	169	118	0.214
Bakelite	79.5	0.134	0.38
Brass	530	64	0.082
Copper	559	223	0.092
Earth (coarse)	128	0.30	0.44
Glass Wool	12.5	0.023	0.16
Iron/Steel	485	30	0.11
Nickel	556	52	0.107
Polyurethane Foam	1.8	0.015	-
Rubber	60	0.09	0.48
Stainless Steel	500	10	0.11
Tin	456	37	0.054
Water	62.4	0.35	1.00

INSTALLATION OF CAMBION THERMOELECTRIC MODULES



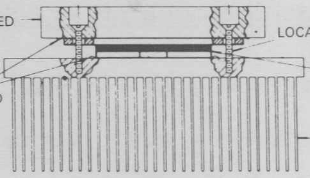
Thermoelectric devices are only as strong as the semiconductor materials used in their fabrication and thus may be damaged by the application of excessive stress. Modules should never be designed as mechanical supporting members of an assembly.

Several mounting methods are available including the clamping of modules between a heat sink and object to be cooled and the soldering or epoxy bonding of the module hot side to a heat sink. Mechanical clamping is generally the preferred mounting technique and soldering is normally used only when other methods are not practical. Epoxy bonding should not be used when operation in a vacuum is required.

CLAMPING METHOD

1) The mounting surfaces between which modules are to be clamped should be ground or lapped flat to within $\pm .001''$.
2) Clean module and mounting surfaces carefully to remove any burrs, grit, etc.
3) If more than one module is to be used in the assembly, all modules in the set must be matched in thickness (height) to within .002" total deviation.
4) Coat the module hot-side with a thin film (.001" typical thickness) of Zinc Oxide loaded Silicone grease (such as CAMBION P/N 630-7208-01-00-00, DOW CORNING type 340, WAKEFIELD type 120, or GE type G641) and place the module on the heat sink. Applying firm but even downward pressure, rock the module from side to side until a slight resistance is felt and excess thermal grease is squeezed out.
5) Coat the cold side of the module with a thin film of thermal grease. Place the object to be cooled in contact with the module and rock the object slightly from side to side to squeeze out excess thermal grease.
6) Bolt the object to be cooled and heat sink together using 4-40 or 6-32 stainless steel screws with Belleville washers or split-type lockwashers. To insure even pressure across the module surfaces, tighten all screws "finger tight" and then continue tightening in an alternate or crosswise pattern starting with center screws (if any) first. Repeat this pattern several times, gradually increasing torque each time. A simple method of estimating correct screw torque is to bring all screws down until they are "snug" (but not tight) and back off approximately one-quarter turn so that the spring action of the belleville washer or split lockwasher can be felt. Maximum recommended compression loading is 15 pounds per square inch of module surface.

CLAMPING METHOD



EPOXY BONDING METHOD

1) Grind or lap the heat sink surface flat and clean and degrease to remove any burrs, oil, grit, etc.
2) Coat the module hot side with a thin layer of thermally conductive epoxy (such as WAKEFIELD "Delta Bond 152").
3) Place the module on the heat sink and rock slightly from side to side until resistance is felt and excess epoxy is squeezed out.
4) Weight or lightly clamp the module to hold it in place until the thermal epoxy has cured.

SOLDERING METHOD

CAUTION: This procedure entails some risk of module damage during installation and moderately close temperature control is required in order to prevent overheating of the module. Other mounting methods should be used whenever possible.

1) Grind or lap the heat sink surface flat and clean and degrease to remove any foreign matter. The heat sink surface must be solderable. I.e., either copper or properly plated aluminum.
2) Tin the module area of the heat sink with a low temperature solder which has a melting point below 125°C. Heat the heat sink surface to 120 to 130°C. Apply flux to the copper pads on the module hot side and place the module in position on the tinned heat sink. Move the module slightly in a circular pattern and, after a few seconds, the solder should wet the module. Surface and excess flux will boil out. NOTE: Any significant resistance to module movement on the heat sink indicates insufficient solder. In this event, remove the module and add additional solder to the heat sink.
3) Allow the assembly to cool and remove all flux residue.

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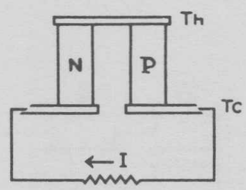
application note

THERMOELECTRIC POWER GENERATION

Although the primary use for thermoelectric devices is in cooling and heating applications, it is also possible to use such devices to generate power by applying a temperature differential across the module face plates. Unfortunately, thermoelectric devices are very inefficient when used in this manner and thus thermoelectric power generators are normally limited to relatively low power sources. However, if waste heat is available, it is possible to obtain small amounts of useful power using thermoelectric modules in the power generation mode. This somewhat oversimplified discussion is designed to acquaint the layman with general concepts of thermoelectric power generation.

Equations for a Thermoelectric Power Generator

Figure I: Conventional Thermocouple Junction



R_L

The open-circuit voltage produced by the temperature difference of Th - Tc is given by the expression $V = \bar{a}\,\Delta T$

where: (1) $\bar{a}$ is the Seebeck coefficient in volts/°C (or °K) at the average module temperature; the average module temperature = Tc + Th / 2. $\bar{a}$ may be obtained from Table I

(2) $\Delta T = Th - Tc$ in °C (or °K)

With a load resistance connected to the thermoelectric couple, the output or load current is expressed by the relationship

$$I = \frac{\bar{a}\,\Delta T}{\bar{R} + R_L}$$

where:

(1) $\bar{R}$ is the internal resistance of the thermoelectric couple in Ohms

(2) R_L is the load resistance in Ohms

(3) . I is the output current (through R_L) in amperes

Because an actual thermoelectric module has a number of individual couples connected electrically in series and thermally in parallel, the equations for a module may be re-written

$$V_{out} = a_m \Delta T = I\,(Rm + R_L)$$

$$I = \frac{a_m \Delta T}{Rm + R_L}$$

where:

(1) a_m is the averaged module Seebeck coefficient in volts/°C (see Table I)

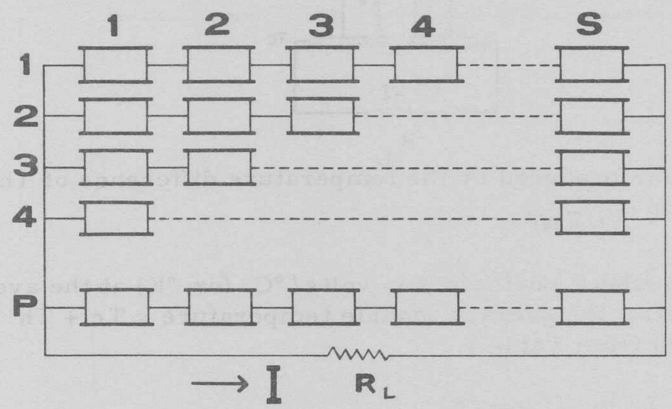
(2) Rm is the averaged module electrical resistance in Ohms (see Table I)

The output power from a module may then be expressed as:

$$PO_{watts} = R_L \left(\frac{a_m \Delta T}{Rm + R_L} \right)^2$$

A practical thermoelectric generator typically contains a number of individual modules electrically connected either in series, parallel, or series-parllel. Consider the generator system shown in Figure II which has N number of modules with S number in series and P number in parallel. Thus N = P x S

Figure II



The current passing through the load resistance R_L is:

$$I = \frac{S\, a_m \Delta T}{\frac{S}{P} Rm + R_L}$$

The power output from the generator is:

$$PO = R_L \left[\frac{S\, a_m \quad \Delta T}{\frac{S}{P} \;\; Rm + R_L} \right]^2 = \frac{N\; (a_m \quad \Delta T)^2}{4Rm}$$

The optimum load resistance is:

$$R_L \text{ opt.} = \frac{S}{P}\; Rm$$

DESIGN EXAMPLE

A 12 volt, 1.5 ampere generator is needed where the temperature conditions of Th = +130 °C and Tc = +30 °C can be obtained.

Solution

It has been decided to use CAMBION P/N 801-2003-01-00-00 Thermoelectric module for the design.

(1) The average module temperature $= \frac{Th + Tc}{2} = \frac{130 + 30}{2} = 80\,°C$

For the P/N 801-2003-01-00-00, at 80 °C (from Table I) $a_m = 0.02819$ and $Rm = 1.643$

(2) The load resistance (R_L) is: $R_L = \frac{V}{I} = \frac{12 \text{ volts}}{1.5 \text{ amperes}} = 8 \text{ ohms}$

(3) The power required for the load is: $P = VI = 12 \times 1.5 = 18$ watts

(4) The maximum output power from one module with the given temperature conditions is:

$$\text{Max. } PO = \frac{(a_m \quad \Delta T)^2}{4Rm} = \frac{(0.02819 \times 100)^2}{4 \times 1.643} = 1.209 \text{ watts}$$

(5) Since the load requires 18 watts, the minimum number of modules required would be:

$$N = \frac{18 \text{ watts}}{1.209 \text{ watts}} = 14.9 \cong 15 \text{ modules}$$

(6) For maximum power transfer into the load (R_L), the generator and load resistances should be matched. To do this, the best series/parallel arrangement of modules must be determined.

Since R_L opt. $= \frac{S}{P}$ Rm, then $\frac{S}{P} = \frac{R_L \text{ opt.}}{Rm} = \frac{8 \text{ ohms}}{1.643 \text{ ohms}}$

$$\text{Thus } \frac{S}{P} \cong \frac{8}{2}$$

(7) In step (5) above was determined that a minimum of 15 P/N 801-2003-01-00-00 modules would be required to obtain the necessary output power. Also, from step (6) it was found that a series/parallel ratio of approximately 8 / 2 is desired in order to optimize power transfer and maximize generator efficiency.

Therefore, if we choose sixteen modules (8 x 2) with two parrallel strings of eight modules in series, both the required output power and output resistance may be obtained.

NOTE: In this example the 8/2 S/P ratio came out to be very close to the total number of modules required and thus it was possible to fairly closely match the load and source resistances. In other designs, it may be found that the total number of modules required and the series/parallel ratio for maximum power transfer are not equitable. When this occurs, it will be necessary to base the design on the number of modules needed for a particular voltage or current and to not attempt to design for maximum power transfer and efficiency.

It can clearly be seen that the output voltage and power from a thermoelectric generator are directly related to the temperature difference across the module. Consequently, the ΔT should always be as large as possible in any generator system, taking into account, of course, the maximum module operating temperature (which is + 150 °C for most CAMBION thermoelectric devices).

One factor often overlooked in a thermoelectric generator design is the performance of the cold-side heat sink. Because of the low generator efficiency - typically 2% or less - a relatively large amount of heat passes through the thermoelectric modules into the heat sink. For example, in a 2% efficient 20 watt power generator, 1000 watts of heat must be supplied to the generator and 980 watts of heat must be dissipated by the cold-side heat sink. As a result, a <u>very</u> efficient cold-side heat sink is required if the generator is to operate satisfactorily. It will frequently be found that the biggest problem in designing a thermoelectric generator is maintaining a reasonable temperature differential because of heat sink limitations.

TABLE I Averaged Module Material Properties

Average Temp. °C	Seebeck Voltage ($\bar{a}$) volts/°C per couple	a_m Seebeck Voltage for Various Modules				Module Resistance (Rm) for various modules				
		801-2001 801-3958 (31 cpl)	801-2003 (71 cpl)	801-1081 (49 cpl)	801- 801- (127 cpl)	801-2001 801-3958 (31 cpl)	801-2003 (71 cpl)	801-1081 (49 cpl)	801-2004 (6amp) (127 cpl)	801-2005 (9amp) (127 cpl)
-100	0.0002511	.007786	.01783	.01231	.03190	.1996	.6857	.2028	1.227	.8177
-90	0.0002632	.008160	.01869	.01290	.03342	.2065	.7094	.2098	1.269	.8460
-80	0.0002752	.008531	.01954	.01348	.03495	.2148	.7379	.2183	1.320	.8800
-70	0.0002870	.008898	.02038	.01406	.03645	.2244	.7709	.2280	1.379	.9193
-60	0.0002986	.009258	.02120	.01463	.03793	.2354	.8087	.2392	1.447	.9644
-50	0.0003100	.009610	.02201	.01519	.03937	.2476	.8506	.2516	1.521	1.014
-40	0.0003210	.009951	.02279	.01573	.04077	.2611	.8970	.2653	1.604	1.070
-30	0.0003316	.01028	.02354	.01625	.04211	.2756	.9468	.2800	1.694	1.129
-20	0.0003417	.01059	.02425	.01674	.04338	.2912	1.000	.2959	1.789	1.193
-10	0.0003512	.01089	.02494	.01721	.04461	.3078	1.057	.3128	1.891	1.261
0	0.0003601	.01116	.02556	.01764	.04572	.3252	1.117	.3304	1.998	1.332
10	0.0003683	.01142	.02616	.01805	.04679	.3433	1.179	.3488	2.109	1.406
20	0.0003757	.01165	.02668	.01841	.04773	.3620	1.244	.3678	2.225	1.483
30	0.0003821	.01185	.02714	.01873	.04855	.3811	1.309	.3872	2.341	1.561
40	0.0003875	.01201	.02751	.01898	.04920	.4006	1.376	.4071	2.461	1.641
50	0.0003918	.01215	.02783	.01920	.04978	.4202	1.444	.4270	2.583	1.721
60	0.0003949	.01224	.02803	.01935	.05014	.4397	1.511	.4468	2.703	1.801
70	0.0003967	.01230	.02817	.01944	.05039	.4591	1.577	.4665	2.821	1.881
80	0.0003970	.01231	.02819	.01946	.05042	.4781	1.643	.4858	2.939	1.959
90	0.0003958	.01227	.02810	.01939	.05027	.4964	1.705	.5044	3.050	2.034
100	0.0003929	.01218	.02790	.01925	.04990	.5140	1.766	.5223	3.159	2.106
110	0.0003882	.01203	.02755	.01902	.04928	.5305	1.823	.5391	3.261	2.173
120	0.0003815	.01183	.02709	.01870	.04846	.5457	1.875	.5545	3.354	2.236
130	0.0003728	.01156	.02648	.01827	.04736	.5595	1.922	.5685	3.438	2.292
140	0.0003619	.01122	.02570	.01773	.04597	.5714	1.963	.5806	3.511	2.341
150	0.0003486	.01081	.02476	.01709	.04429	.5814	1.997	.5908	3.572	2.382

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